High-Contrast Gratings:

A New Platform for Integrated Optoelectronics

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Abstract—**A new concept of dielectric subwavelength grating has emerged. This grating leverages a high contrast in refractive indices for the grating medium and its surrounding (and hence the name). We will discuss how HCG can manipulate light to achieve various extraordinary properties and its potential as a new platform for integrated optics.**

Keywords-component; subwaveelngth gratings, VCSELs, integrated optics (key words)

I. INTRODUCTION

Recently, we reported extraordinary properties from a simple, one-dimensional, single-layer, subwavelength grating fully surrounded by media that has a large contrast of refractive index (Fig. 1) [1-4]. Leveraging this large index contrast with subwavelength dimensions, light can be manipulated in ways that were totally unexpected. The different designs that will be reviewed in this talk include (a) broadband, high-reflectivity mirror for light incident in surface-normal direction and at a glancing angle [1-4], (b) ultra high-Q resonator with surface-normal output [5], (c) as a cladding for an ultralow loss hollow-core waveguide [6-8], and (d) ultra-compact optical coupler and splitter [9,10]. The prospect for HCG as a new platform for integrated optics will be discussed.

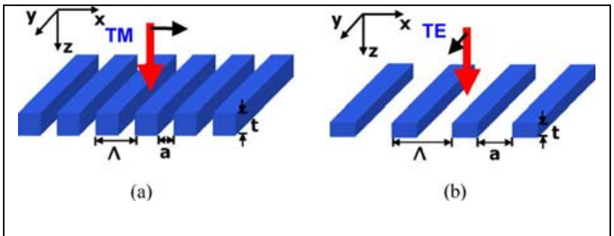

Figure 1. Schematic of high contrast grating (HCG). High index gratings (blue) are fully surrounded by low index material. They can be designed to reflect primarily TE or TM waves.

II. 2. BASIC PRINCIPLE

The origin of high reflectivity can be understood by noting that when a light beam is incident on an HCG, the light is reflected and transmitted into multiple diffraction orders. However, when the period of the grating is less than the wavelength ($\Lambda<\lambda$), all higher order modes are evanescent in air (low index medium). When the grating parameters are optimally designed, destructive interference is obtained between the directly transmitted waves, which leads to an extremely high reflectivity. Due to the high index contrast between the gratings and their surroundings, there are only two modes of significant energy [11]. Hence, the matching of boundary conditions to result in constructive interference can be satisfied over a broad wavelength range, leading to an enormously broadband high reflectivity $\Delta\lambda/\lambda$~65%. With a simple change of parameters to yield destructive interference also at the input plane, on the other hand, an extremely narrow band resonance can be attained $\Delta\lambda/\lambda\sim10^{-6}$. Though both are a direct result of interference, the design tolerance is remarkably large due to the large index contrast [3,4].

III. BROADBAND MIRRORS

Broadband mirrors with very high reflectivity are the fundamental building block for numerous device applications, including lasers, modulators, detectors, sensors and imaging, ranging from 0.7µm to 12µm wavelength regimes. Semiconductor-based distributed Bragg reflectors (DBRs) have been used to achieve high reflectivity required for devices such as vertical cavity surface emitting lasers (VCSEL), detectors and filters. Because of the very short gain length in VCSELs, a very high reflectivity (>99%) is required in the DBRs. Hence, the DBRs are typically very thick, consisting of 20-40 pairs of alternating index materials. This has been the most critical bottleneck for the realization of VCSELs in wide wavelength regimes.

The fact that HCG was suitable to be used in the near-field regime was not proven until its incorporation in a VCSEL as the top mirror [3]. Figure 2 shows the schematic of a typical HCG-VCSEL. The device consists of a conventional semiconductor-based bottom *n*-DBR mirror, a λ-cavity layer with the active region, and an HCG-based top mirror. The structure of the HCG consists of periodic stripes of $Al_{0.6}Ga_{0.4}As$ that are freely suspended with air as the low-index cladding layers on the top and bottom. Typical single mode with 40 dB side mode suppression ratio is routinely obtained for both designs. Lithographically defined polarization was demonstrated with a mode discrimination as large as 25-36 dB. Extraordinarily large fabrication tolerance is demonstrated with ±20% variation of the HCG critical dimension. Emission wavelength of HCG-VCSEL varied only 0.2% with 40 % change in lithography linewidth.

The HCG is naturally suitable for forming a tunable VCSEL structure. With its ultra-thin layer, 20-40 times thinner than a typical DBR, the other two dimensions of the micro-electro-mechanical (MEM) structure can be reduced by similar numbers, resulting a 1,000-8,000 times mass reduction and >160 times increase in tuning speed. We demonstrated a tunable VCSEL with a tuning range of 18 nm and tuning speed ~20 ns, the fastest MEM tunable device reported to date.

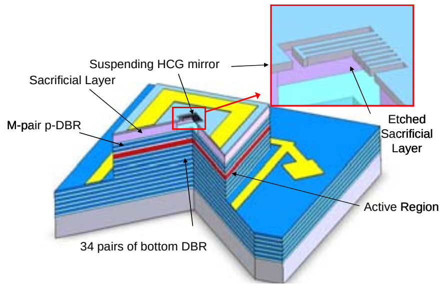

Figure 2. Schematic of HCG-VCSEL

IV. High Quality Factor (Q) Resonators

High Q resonators have attracted much attention recently. Grating structures including distributed Bragg reflectors (DBRs) and distributed feedback (DFB) structures have been widely studied as optical resonators, in which the incident beam, resonance optical mode and optical output are all collinear. While this configuration facilitates device integration in a cascaded fashion, they are often difficult to couple with free space or fiber optics. Recently, we present a novel high-Q resonator using the high contrast subwavelength grating concept (Fig. 3). The in-plane high-contrast grating forms a high-Q resonator which couples light in the surface-normal direction. Unlike our previous HCG work, the HCG design presented in this paper offers a narrow band high-Q resonator instead of a broadband mirror. A Q-factor of ~500,000 is obtained from numerical simulation. Experimentally, a Q-factor of 14,000 is measured from fabricated devices. The design shown in this paper can be potentially used to make a simple surface-emitting laser.

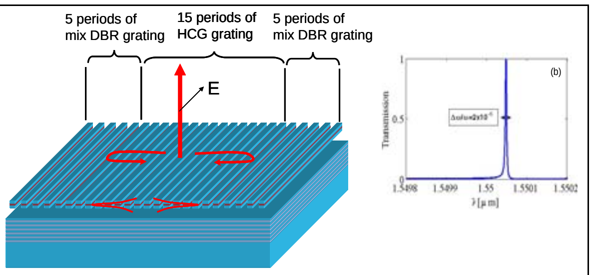

Figure 3. HCG Resonator and calculated spectrum

V. Hollow-core Waveguide

The ability to generate long optical delays with low intrinsic loss is useful for a wide range of applications including optical signal processors, RF filtering, optical buffers, and optical sensing. Lithographically defined, chip-scale waveguides are compact, light-weight, and can be integrated with other optoelectronic devices. The lowest reported loss achieved to-date in chip-based waveguides is ~1 dB/m. Hollow-core waveguides are highly promising for achieving ultra-low loss, nonlinearity and dispersion because of the elimination of the core material. There have been advances in hollow-core waveguides using a metallic shell, DBR, or photonic crystals, etc. The basic principle is to guide the optical beam propagating through air by multiple reflections at the cladding mirrors. The lowest loss for a chip-based hollow-core waveguide is still high because the reflectivity of the cladding DBR not being high enough. Ultrahigh reflectivity is essential to achieve ultra-low loss. We propose using HCGs as the high reflectivity cladding to reflect light at a small glancing angle (Fig. 4). The most peculiar property, perhaps of all, is that HCG with periodicity parallel to the direction of propagation can confine light in the waveguide. Instead of causing backward wave reflection normally expected of traditional periodic structures, the HCG forms a high reflectivity glancing incidence mirror for the guided wave. We show a HCG hollow-core slab waveguide design with an exceedingly low propagation loss (<0.01 dB/m) using numerical simulation [6,7]. Preliminary experimental results indicate that HCG may be used to control polarization dependent dispersion [8].

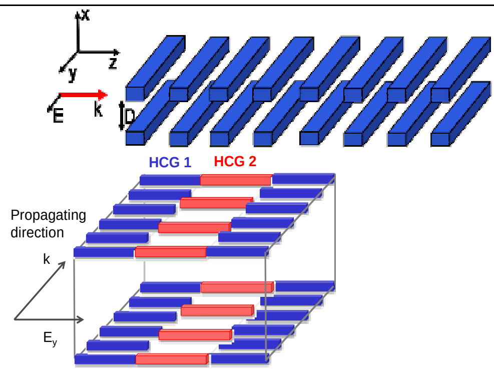

Figure 4. 1D (top) and 2D HCG hollow-core waveguide

VI. Ultra-compact Optical Coupler and Splitter

As light is tightly confined by HCG-HW, it can be shown that two adjacent, parallel hollow-core waveguides sharing one common layer of HCG can be totally isolated. This means the two waveguides are separated by a dimension less than 1 λ, in sharp contrast to conventional waveguides needing a separation up to ~10λ. Leveraging this phenomenon, we can construct an ultra-compact 3dB splitter and 2×2 coupler.

An extremely compact 2×2 coupler with a length of 26um (16 λ), and a footprint (length×width) of 85um^2 (35 λ^2) and a 3dB splitter with a length of 3.6um (2.4 λ), and a footprint of 12 um^2 (5 λ^2) are realized with finite-difference time-domain (FDTD) simulation. Low insertion loss is obtained through the coupler (~0.35dB) and the splitter (~0.28 dB). The design presented [9] can be easily extended to form a variety of on-chip photonic components (N×M couplers, arbitrary ratio splitters) that are useful for optical signal processing and routing applications.

For a 2×2 coupler, the coupling length can be expressed as: $L_{MMI} = 4n_r W_{MMI}^2 / \lambda_o$, where n_r is the refractive index of the core and W_{MMI} is the effective width of the MMI region [12]. Similarly for a 3dB-splitter, $L_{MMI} = n_r W_{MMI}^2 / 2\lambda_o$. For conventional waveguide design, the input/output waveguides have to be separated by at least $w \sim 2w$, w being the width of each waveguide, to avoid unwanted coupling. Hence, the width of the MMI region becomes $3w \sim 4w$. For the case of hollow-core waveguide, the refractive index of the core is 1 and more importantly stronger confinement of light in the core region means that the waveguides can be literally adjacent to each other. In this case, the width of the MMI region is reduced to $2w$. These two factors contribute to a large reduction in the area of the splitter and the coupler by a factor of 10 (see Table 1). Figure 5 shows the results of a splitter for a 1.5um waveguide. As we can see from the figure, light is indeed strongly confined to the core and there is negligible coupling between the output waveguides. The coupling length in this case is 3.6um (2.4 λ) giving rise to an extremely small device footprint of 12um^2 (5 λ^2).

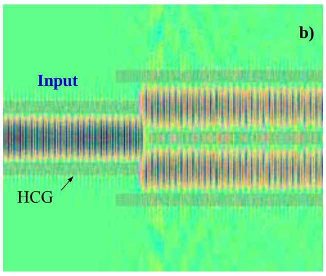

Figure 5. Finite-difference time domain simulation showing the splitting of light in a HCG-HW based MMI splitter.

Quantity	Conventional waveguide	HCG hollow-core waveguide
n_{core}	1.5 - 3	1
W_{MMI}	$3w - 4w$	$2w + t_{HCG}$
$L_{Splitter}$	$\sim 12*(w^2/\lambda_o)$	$\sim 2*(w^2/\lambda_o)$
$L_{Coupler}$	$\sim 100*(w^2/\lambda_o)$	$\sim 16*(w^2/\lambda_o)$
$A_{Splitter}$ ($W_{MMI} * L_{splitter}$)	$\sim 40*(w^3/\lambda_o)$	$\sim 4*(w^3/\lambda_o)$
$A_{Coupler}$ ($W_{MMI} * L_{Coupler}$)	$\sim 300*(w^3/\lambda_o)$	$\sim 30*(w^3/\lambda_o)$

Table 1. Comparison between conventional waveguide MMI splitter/coupler with a HCG hollow-core waveguide MMI splitter/coupler of same waveguide width w. Low refractive index of the core and stronger confinement of light in the core region leads to a factor of 10 reduction in the footprint of HCG based splitter and coupler.

VII. Conclusion

The HCG can potentially be a new platform to revolutionize chip-scale integrated optics. We envision many other novel devices including power combiner, WDM multiplexer, demultiplexer, optical modulators, fixed and tunable filters, and resonators to be built on the same platform. The HCG-HW can be highly useful for sensing applications as well as a vehicle for nonlinear optics experiments, having the unique property of confining a high optical intensity in the middle of a core that can be filled with anything desirable.

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